HISTORY OF THE SUN

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Summary

To achieve realistic estimates of sustainable development perspectives it is also necessary to be aware of the general background conditions in the solar system, including the Sun itself. Therefore, we briefly discuss here the Sun's history, development, structure, its production of energy, its supplies, and its probable development. The Sun and its steady radiation, with maximum intensity at the region of optical wavelengths, constitute one of the principal conditions for life on Earth. On the other hand, not only the hard X-ray and UV radiation produced by the quiet Sun, but also many manifestations of solar activity—especially the effects related to flares and coronal mass ejections—represent a certain threat, or at least some disturbances and limitations, for life and civilization on Earth. These dangers apply particularly in the event of weakening of the protecting layers of Earth's atmosphere, and for astronauts in orbit.

The Sun, as our nearest star, is a large representative of matter in the state of plasma. It is an important object and also a natural laboratory, which can be studied in order to

understand the properties of matter in extreme conditions. Here we summarize some of the knowledge that is currently considered as "settled." Other current questions and problems, raised a long time ago or quite recently, concerning the relations and explanation of various existing periods of solar activity, models of the solar dynamo, missing neutrinos, flare mechanisms, and so on, are discussed very briefly or even avoided in this contribution.

1. Introduction

Our entire galaxy consists of 150×10^9 stars. One of them, the Sun, is situated at the central plane of the galaxy at a distance of 10×10^3 parsecs from its center. The orbital velocity at this distance is ~250 km^{-1} and the corresponding orbital period of the Sun (called a galactic year) is 260×10^3 y. The Sun is an ordinary star distinguished only by being the nearest one to Earth. In contrast to many, if not most, stars, the Sun is a single star. In other words, it is not a member of a binary or multiple star system; and unlike most star systems, it possesses a planetary system. The Sun's only known point of uniqueness consists in its responsibility for our existence. There is no energy source, fossil or renewable, other than nuclear fusion and nuclear fission, which does not derive directly or indirectly from the Sun. Nuclear reactions occur inside the Sun converting hydrogen into helium and providing the solar energy upon which we depend for our existence. The amount of solar energy of all wavelengths received at the mean Sun–Earth distance—the solar irradiance—is 1368 $W{\cdot}m^{-2}$. The total human consumption of energy is ~10^{13} W at the present time. Let us suppose we can convert the solar radiation energy falling on Earth into electrical energy with an efficiency of only 10%. Then a total area of collectors placed close to the equator (to minimize the effect of inclination) corresponding to a circle with diameter of ~700 km would be sufficient.

The Sun is a sphere of plasma held together by a balance of its own self-gravitation and other forces, mainly the pressure of radiation. It is kept hot by the steady nuclear reactions happening in the solar core. The radius of the Sun is 109 times larger than that of Earth; the mass of the Sun represents more than 99.8% of all the solar system mass and is 333 000 times greater than the mass of our home planet.

2. Principal Characteristics

Characteristic	Value
Mass	1.989×10^{30} kg
Radius	6.9599×10^5 km
Mean density	1.409×10^3 $kg{\cdot}m^{-3}$
Core density	1.48×10^5 $kg{\cdot}m^{-3}$
Luminosity	3.86×10^{26} W
Effective temperature	5780 K
Core temperature	15.6×10^6 K
Age	4.6×10^9 y
Rotation period	25–35 d
Magnetic field	0.1–0.4 T

Escape velocity (at photosphere)	6.177×10^2 km·s^{-1}
Freefall acceleration at surface	2.74×10^2 m·s^{-2}
Chemical composition (number of atoms)	91% H, 9% He, 0.1% other
Chemical composition (mass)	71% H, 27% He, 2% other
In relation to Earth	
Mean distance	1.496×10^8 km
Minimal distance (~January 3)	1.471×10^8 km
Maximal distance (~July 7)	1.521×10^8 km
Angular size (at mean distance)	31.99°

Table 1. Characteristics of the Sun

3. Biography of the Sun

There is no direct evidence about the formation of the Sun. Nevertheless, observations of other stars as well as of the small bodies of the planetary system, together with theoretical astrophysics and particle physics, have made it possible to answer most questions that have been raised about the solar biography.

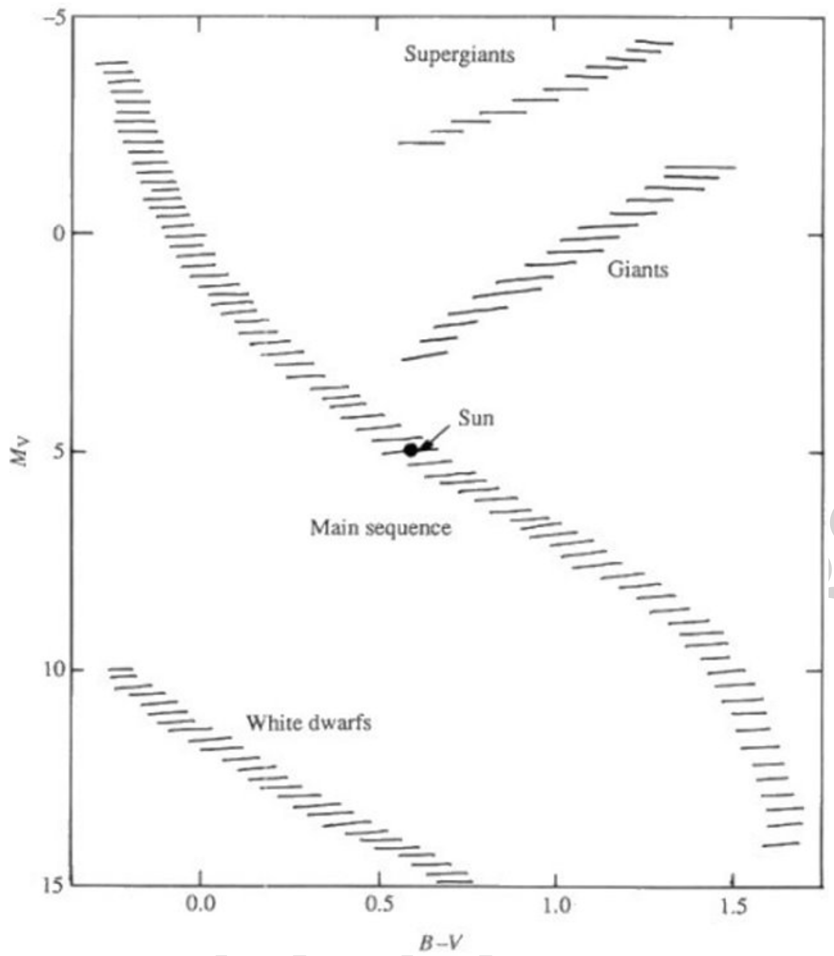

Figure 1. Hertzsprung–Russel diagram
The Hertzsprung-Russel diagram displays the visual magnitude M_V of stars against the color index B-V.

We can distinguish four different stages in its life. They concern its predecessors, its childhood as a protosun or a solar globule, and then its present mature stage as a main sequence star. Theoretical models describe the processes of the Sun's birth as a star. These models also have to approximate the Sun's present characteristics such as its observed radius, luminosity, and chemical composition after an elapsed time corresponding to the Sun's estimated age. If the approximation fits the observed status well, one can also make qualified estimations concerning the future stages of the Sun.

The concept of the Hertzsprung–Russel (H–R) diagram is indispensable. When we derive the luminosity and the effective temperature for individual stars and plot them in a diagram, we can see the stars distributed not homogeneously, but in certain characteristic sets. The most simple form of the H–R diagram displays stars of known distance in the frame depending on their visual magnitude M_V (a logarithmic function of the star luminosity) and their B-V color index (a function of the effective temperature). Effective temperature along the *x*-axis rises from right to left, while the luminosity rises along the *y*-axis from bottom to top. The further right a star's data point is located, the more cold (reddish) it is, and the higher its data point, the larger its luminosity and its geometrical size. We can see four main groups of stars, from hot white dwarfs to rather cold supergiants. Most stars are located on the main sequence. The Sun is displayed approximately in the center of both the H–R diagram and of its main sequence. This means the properties of the Sun are rather close to the mean, and common among the other stars. During their lifetimes, and depending on their initial mass, stars develop and move along certain possible trajectories in the H–R diagram. Therefore, from the fact that the vicinity of the position of the Sun is highly populated, we can conclude that this part of the main sequence contains steady stars and that they remain there for a long proportion of their star life.

3.1. Predecessors of the Sun

The contemporary Sun is a part of our galaxy and is located at a distance of 30 000 light years from the galaxy's center. As the age of the Sun (4.6×10^9 y) is less than that of the galaxy (10^{10} y), the Sun must have been formed from a cluster of a local intergalaxian gas and dust. The first generation of stars were formed from collapsing clouds of gas whose chemical composition was the same as clouds made in the big bang explosion: mostly hydrogen with a small amount of helium but no heavy elements. The oldest stars in the Galaxy, still mostly concentrated in the galactic halo, still have a low abundance of heavy elements like carbon, oxygen, and iron. These elements are just being created in these star cores, and have not existed in them before. The chemical composition of our planetary system, formed at the same time as our Sun, provides evidence that heavy elements had to be present at the time of the formation. From theoretical astrophysics we know that the only way to create chemical elements with higher mass numbers is by nuclear fusion in the cores of stars. Therefore, the initial material of our solar system was processed in massive stars. As star luminosity is proportional to the fourth degree of the star mass, stars that were 4–8 times more massive than the mass of the Sun exhausted their nuclear sources of energy very quickly and afterwards ended up as supernovas. During the process of their explosion their atmospheres were ejected and spread far into space. But only these massive stars could have produced the initial material, with large amounts of heavy elements, that could have been used in the formation of the subsequent star generation that included our Sun and its planetary system. The predecessors of the Sun exploded during supernova events $\sim 2 \times 10^7$ years before the Sun's formation; their possible remnants, probably white stellar dwarfs, have not yet been identified.

3.2. From the Interstellar Globule to the Protosun

It took 10^7 y after these supernova explosions for this initial material to lose its excentrical momentum, spread out into space, and become mixed together to the mean density of hydrogen atoms 6×10^5 m^{-3} that is typical in the interstellar medium. Even if these interstellar clouds contained enough mass (10^{56}–10^{59} atoms and molecules), they also required some kind of an instability to trigger the mass concentration and accretion from gravitation that would produce a protosun globule. Such a mechanism may be provided by pressure of gravitation of a close star with high luminosity, by a shock wave after a supernova event, by passing a nearby star, or by crossing a galactic potential barrier, etc. These mechanisms would have also had to overcome the turbulent motions and the magnetic field that tried to prevent the contraction of the primordial interstellar nebula into a globule. Such a solar globule acts as an enormous supply of gravitational, nuclear, electromagnetic, and kinetic energy. The entire further development of the globule is determined by the internal tendency of the globule mass to get rid of its energy. The contraction, and associated decrease in size of the globule created a gravitational energy release concentrated close to its center. Half of the released energy converts into kinetic energy of particles, in other words, heat. This heating then results in convection, which transports energy from the center of the globule to its surface. The other half of the released gravitational energy is converted into radiation. Heating of the globule leads to temperature increase. The radiation maximum then shifts from radio band into infrared and into the visible region with the increasing temperature. Thus, this transport of released energy from the globule/protosun center to its surface is performed by convection.

The protosun becomes an infrared and later a red giant. Because of its large size, its luminosity is several hundred times larger than that of the present Sun. This radiating protosun is located in the right and upper part of the H–R diagram. At that time, the protosun was surrounded by a large and hot corona. Its activity was much larger than our Sun at present and together with a mighty solar wind, it influenced the conditions in the forming planetary system. The intensive solar wind and the bright ultraviolet and X radiation removed the primary atmospheres from the internal protoplanets Mercury, Venus, Earth, and Mars. When the protosun's surface temperature reached 3×10^3 K, energy began to be transported from the core to the protosun surface by radiative transfer in addition to convection. The temperature of the core continued to rise and when it became 7×10^6 K, thermonuclear fusion in the core appears as a source of energy comparable to the heating from gravitational contraction. Then, as temperature in the core rose further to reach 13×10^6 K, the pressure of the plasma stopped the contraction. The thermonuclear fusion of hydrogen into helium became the exclusive source of solar luminosity. At that time, the radiating protosun moves onto the main sequence in the H–R diagram and becomes an ordinary star: our Sun. The time interval from the interstellar cloud phase to the Sun's emergence as a main-sequence star can be estimated at 10^6 y if we assume that its luminosity is constant through this time and that half of its gravitational energy was converted to heat and irradiated.

3.3. The Sun as a Main-sequence Star

Once the Sun reaches the main sequence in the H–R diagram, its luminosity is ensured by its nucleus supply of hydrogen which continuously converts to helium during the proton–proton (pp) cycle at its core. More massive stars than the Sun have greater temperatures in their cores. At core temperatures higher than 16×10^6 K, different types of nuclear fusion occur, such as the carbon–nitrogen (CN) cycle. Such mechanisms are more effective, but the available hydrogen supply is spent in a shorter time period. According to realistic estimations, it will be another 5×10^9 y before the Sun depletes the usable hydrogen in its core at its present consumption rate.

Had the Sun a three times greater mass, then converting all the hydrogen in the core to helium by the CN cycle at a vastly higher rate would take ~10^7 y. The rate of nuclear fusion in the core is self-regulated by a balance between the pressure of radiation and the gravitational pressure caused by the higher levels of solar mass being attracted centerward. The Sun will be close to the main sequence until it is about twice its present age. The uncertainty in this time estimation is due to doubts concerning the precise amount of helium in the protosun, estimates of which range between 24 and 28 percent by mass. The higher the helium content, the less hydrogen there is to be converted into helium before the Sun leaves the main sequence.

3.4. Future of the Sun

When the usable supply of hydrogen in the Sun's core decreases, the central parts will be almost entirely composed of helium. As the pressure of radiation produced in the core decreases, the core begins to collapse under its own gravity and to heat up intensively. However, the temperature is not yet high enough to start further thermonuclear reactions and the helium remains inert. Increased temperature hits the regions outside the helium core where there is still hydrogen; this hydrogen enters into hydrogen nuclear reactions starting at higher layers. The helium core becomes hotter and denser. The luminosity of the Sun increases as its higher levels expand. The expansion causes the Sun's envelope to become less dense and cooler, which means that the surface effective radiation decreases and consequently the maximum of radiation shifts to a more red color. The Sun leaves the main sequence in the H–R diagram and enters the set of red giants. Its size increases to encompass the present orbit of Mars and all the small planets, including Earth, will terminate in the rarefied red atmosphere of the Sun. All of the Sun's post-main-sequence evolution other than its final dying state is expected to take more than ~10 percent of its lifetime at the main sequence. At the top of the red giants' branch, the helium core is heated to a temperature of 10^8 K and helium—the former trash—is ready to act as a fuel in a higher type of nuclear synthesis producing heavier elements such as beryllium, carbon, and oxygen. After several rather short trials to release all the available nucleus energy in higher reactions of nuclear synthesis, this process will cease owing to lack of fuel and an insufficient temperature for starting the next type of thermonuclear reaction. The Sun will terminate as a planetary nebula, a hot and compact but small star, or white dwarf, surrounded by an expanding shell of tenuous gas. Thus, some 10^9–10^{10} y from now, a small ball of hot degenerated gas with diameter comparable to that of Earth (10^4 km) but with an abnormal density (10^9 kg·m^{-3}) will remain as a remnant of the former Sun and solar system.

4. Structure of the Sun

The chemical composition of the Sun is thought to be practically homogeneous from center to surface. However, from the point of view of physics the Sun's sphere consists of several different layers, each of which plays a completely different role in the production or transfer of energy. While some layers have been regularly observed directly for a long time, others have been studied either theoretically (the core and the convective zone) or occasionally (the corona, during solar eclipses). Recently in new methods of observation, both ground-based and space-borne instruments have been used with remote sensing or *in situ* measurements to obtain new information about each layer of the Sun. From the deep core to the distant rarefied corona and even the solar wind, plasma and magnetic fields penetrate far into the solar system.

	Location[a] (km)	**Thickness (km)**	***T* K**	**ρ (kg m^{-3})**	***n*[b] (particles m^{-3})**
Core	0–5 × 10^5	5 × 10^5	15.6 × 10^6	1.48 × 10^5	—
Convective zone	5–7 × 10^5	2 × 10^5	10^6	10^1	—
Photosphere	—	300	6 × 10^3	2 × 10^{-4}	10^{11}
Chromosphere	—	1500	10^4	3 × 10^{-9}	10^7
Inner corona	—	100 000	1.5 × 10^6	10^{-12}	3 × 10^3

[a]in relation to the center of the Sun

Table 2. Parameters of the Sun's primary layers

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Biographical Sketch

Pavel Kotrč, born in 1948, was graduated from the Faculty of Sciences, Masaryk University at Brno (Mathematics and Physics) in 1972. Since then he has been working as a staff member at the Solar Department of the Astronomical Institute of the Academy of Sciences of the Czech Republic in Ondřejov. In 1980 he obtained his Ph.D. in astrophysics and solar physics. Several longer missions abroad include ISZF Irkutsk, Russia; Hvar Observatory, Croatia; Crimean Observatory, Ukraine; National Solar

Observatory–Sacramento Peak, USA; and Observatoire de Paris, Meudon, France. Research topics include solar atmosphere, flares, surges, prominences, coronal loops, spectral observation, and analysis; diagnostics of the solar activity phenomena; and instrumentation. Kotrč has been principal investigator, coprincipal investigator or co-investigator on several solar physics projects. Since 1992 Kotrč has been an external lecturer on spectroscopy at the Charles University at Prague, since 2000 an external lecturer on solar physics at the Masaryk University et Brno and supervisor of student diploma theses. Kotrč is also a member of the International Astronomical Union and an alternative representative of the Czech Republic in JOSO. He is author and co-author of about 90 papers.